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Performance of Masks and Discussion of the Inactivation of SARS-CoV-2

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Abstract

Meltblown (MB) microfiber fabrics after electrostatically charging are used as the filtering piece in medical masks and N95 respirators. Using this material, the required filtration efficiencies (FE) of bacteria, virus, and submicron particles are satisfactorily met mainly by the electrostatic attraction of the particles on the fiber surface by the charges embedded in the fibers at a low pressure drop (DP) with high breathability across the mask. The masks are initially manufactured for a disposable one-time use. However, if there is a shortage, inactivation of the virus on the contaminated masks to reuse is possible. Several inactivation methods are discussed in terms of their efficacy to kill the virus and the integrity of the mask in terms of loss of FE and the deformation of the respirators. In this paper, SARS CoV-2 and COVID-19 are used interchangeably.

Keywords: Medical masks; N95; Meltblowing; Electrostatic charging; Corona charging; Corona virus; COVID-19; SARS CoV-1; SARS CoV-2; Filtration Efficiency.
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Dr. Peter Tsai, Ph.D. in Material Sciences, The University of Tennessee (UT) has devoted to research and development of electret-making technologies and meltblown microfiber materials for air filter media over 35 years. His above technologies have been used among the industries worldwide producing tens of billions of N95 or equivalent respirators. He was the only recipient of the UT Innovation Awards for three times in its history.

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1. Introduction

Microfiber material is commonly used as air filter media thanks to its high filtration efficiencies (FE) from high fiber surface area and low pressure drop (PD) from its porous structure. Electrostatic charging is employed to improve its FE by 10-20 times without adversely increasing its PD. Meltblowing (MB) is a process to make microfiber nonwoven fabrics. The media thus made it suitable for a variety of air filter applications. This electrostatically charged medium has been used in making medical face masks and N95 respirators. There is an immense demand and a huge shortage of the masks at present to fight with COVID-19 (SARS-CoV-2). Medical masks and N95 respirators are designed and recommended as disposable for one-time use. Inactivation and the reuse of the respirators become necessary when the demand highly surpasses the supply. However, while inactivation requires to kill the virus, the charges must be retained and their integrity must be maintained. This article will address the performance of the masks, the properties of the electrostatic charges, and the degradation of the charges before and after possible treatments of inactivating the virus.

2. Medical face masks and N95 respirators

2.1 Performance of medical face masks and N95 respirators

The FE values of both face masks and N95 Respirators are mainly contributed by the middle layer of electrostatically charged MB fabric. The specifications of US medical masks are listed in the ASTM F2100[1] as shown in Table 1. There are three levels based on bacteria and submicron filtration efficiencies as well as the capability to stop the blood penetration. The bacteria filtration efficiency is tested according to the ASTM F2101[2] using Staphylococcus aureus having the size in the range of 3 μm at a flow rate of 28.3 lpm (1 ft^3/min). The FE of submicron particles is tested based on ASTM F2299[3] using particulate latex spheres. The resistance to Penetration by the Synthetic Blood is tested based on ASTM F1862.[4] The "F" class in ASTM is life-related testing standards.

Table 1. Performance of medical face mask materials.

Performance	Level 1	Level 2	Level 3
Bacteria FE (%)	≥95	≥98	≥98
DP (mmH_2O)	≤5.0	≤6.0	≤6.0
Submicron particulate FE (%)	≥95	≥98	≥98
Res to blood penet (mm Hg)	≥80	>120	≥160
Flame spread	Class 1	Class 1	Class 1

2.2 Characteristics of N95 respirator

Certified by National Institute for Occupational Safety and Health (NIOSH) according to 42 CFR Part 84,[5] N95 is defined as a respirator, not a mask. It is one of the nine types of non-powered particulate filtering respirators. The "N" stands for "Not resistant to oil" and "95" means that its FE is equal to or greater than 95% challenged with NaCl particles having a number average particle diameter of 0.075 μm at 85 1pm flow rate. There are higher levels of N99 and N100 having FE of 99% and 99.97%, respectively. There are also "Resistant to oil" type, R95, R99 and R100, and "Proof to oil" type, P95, P99, and P100. This standard was published on June 8, 1995. There are three models of European respirators, FFP1, FFP2, and FFP3 having FE of 80%, 94% and 99%, respectively, according to EN143 and EN 149 standards published in April 2001.[6,7] After that, other countries followed and issued similar medical mask and respirator standards. The Chinese Standard for KN95, equivalent to N95, is GB2626-2006.

Required by Occupational Safety and Health Administration (OSHA), the N95 respirator was developed to protect industrial operators working in the dusty environment. Around 1996, it was recommended by Centers for Disease Control and Prevention (CDC) to wear by health care workers (HCWs) when taking care of patients with airborne diseases such as tuberculosis. Later on, it was recommended by World Health Organization (WHO) to protect health against severe acute respiratory syndrome (SARS), Middle East Respiratory Syndrome (MERS), Bird Flu caused majorly by H5N1 and H7N9, and Swine Flu caused by H1N1, etc,

The structural difference of medical mask and N95 respirator is that the former is composed of three folded plies of fabrics with a loose edge fitting while the later has a better filtering layer and the requirement of tight edge fitting. Medical masks serve the job to stop large droplets from inhaling and to prevent exposing of the virus by an infected patient. However, it has 80% of submicron FE, less capable of filtering out the suspended fine droplets, and its loose edge fitting leads to 40-60% of the air inhaling through the gap between its edge and the face. On the other hand, besides the higher FE for fine particles or droplets, N95 is designed to fit a body's facial shape providing a tight seal around the face, little air leakage on its edge if worn properly and correctly.

Medical face mask is cleared by Food and Drug Administration (FDA) according to 21 CFR 878.4040[8] for biocompatibility requirement as Surgical Masks and N95 as Surgical N95 Respirators (N95s).

3. Particle filtration mechanism, electrostatic charges, and electrostatic attraction mechanisms

One way of the corona charging, as invented by Tsai, *et. al.*,[9] is a very common method to make electret for air filters including medical masks and N95 respirators. MB is a nonwoven process that makes microfibers having diameters in the range of 2 μm directly from polymer resin. For a given weight of nonwoven fabric, the finer the fiber diameter, the higher the total fiber surface area, and hence the better the FE. In contrast to liquid filtration mechanism, in which the filtration comes from the smaller pore size to block the larger particles, the efficacy of air filtration contributes from the attraction of particles by the fibers on their surface. Fig. 1 shows a 2,000× SEM image of fine particles attracted on the fiber surface, not the blocked particles by smaller pores. The pore size, which is the distance between two fibers, in a MB nonwoven fabric for face mask media, is around 20 μm. However, submicron particles are captured.

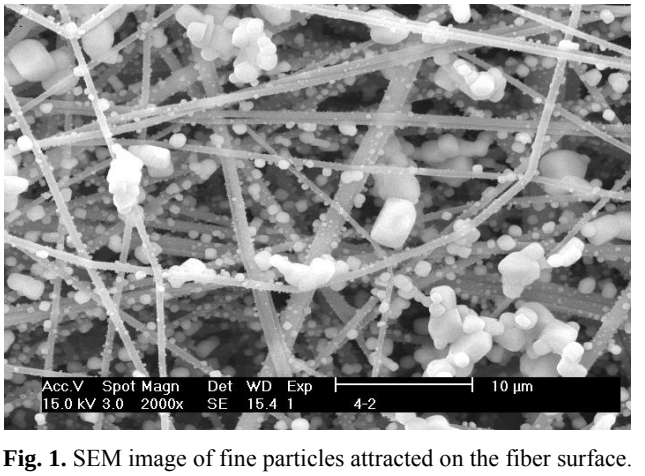

Fig. 1. SEM image of fine particles attracted on the fiber surface.

Both medical masks and N95 respirators are composed of an electrostatically-charged MB fabric as the filtering piece. The increased FE of the MB fabric is ten folds by electrostatic charging compared with the uncharged one. In electrostatic charging, the charges are embedded deeply inside the fibers forming an electret that exhibits a quasi-permanent electrostatic field in contrast to a magnet that exhibits a permanent magnetic field. During the corona charging process, the high voltage electrical field ionizes the air, accelerates and forces the positive or negative charges into one side of a fiber while the opposite polarity of charges is induced into the other side of the fiber leading to a bipolar structure on the fabric as shown on the plots in Fig. 2. The uncharged fabric carries slightly negative charges from polymer processing by friction, positive on one side and negative on the other side of the charged fabric. In each plot, 400 data at the interval of one inch between two points were taken along the machine and the cross directions (MD and CD). MD is the fabric moving direction and CD is the direction across the width of the fabric. The unit of the surface charge potential is in volts as shown in the Z-axis.

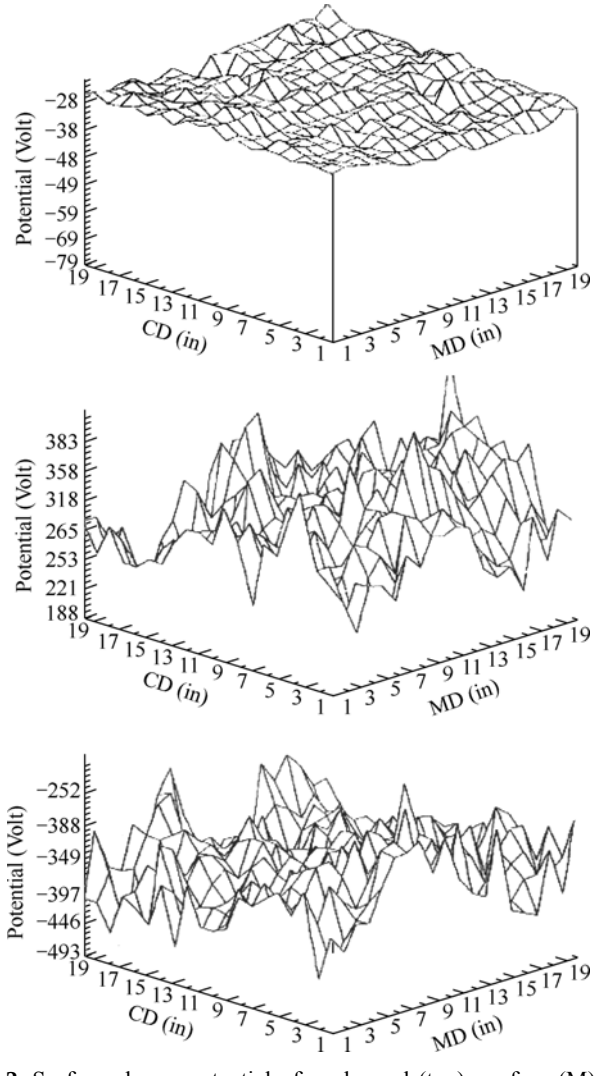

Fig. 2. Surface charge potential of uncharged (top), surface (M) and screen sides (bottom) of charged MB media.

Positive charges attract negative particles and vice versa by Coulombic force. The neutral fine particles can be polarized by the bipolar electric field between two fibers with opposite charges, becoming partially positive on one side and partially negative on the other side of the particle. The partially positive side is captured by negative charges and vice versa. This attraction force is image force by induction. Therefore, an electret is highly effective to capture bacteria, virus, fine particles, and smog, etc. with very high FE.

As the electrostatic charges are embedded deep inside the fibers, they will not dissipate into the environment at a high humidity condition, nor in contact with water or metal materials, suggesting that the charges will retain when the respirator is splattered by water droplets in a rainy day. However, depending on washing methods, problems may arise due to the effect of mechanical forces on the fibrous material causing the material damage and charge decay. It is ineffective in disinfecting the virus by only water washing. According to CDC's instruction, it requires to wash hands with soap water for at least 20 seconds to wash off the germs. The loss of charges by washing masks with soup water will be discussed in IV. 3.

There is an unnoticeable charge decay of a face mask at ambient conditions such as at 25 °C for a lengthy period of time. The decay at elevated temperature such as at 70 °C for 24 hours as indicated in Fig. 3, simulating the charge decay at ambient conditions of shelf time for five years, is slow to guarantee a long-life storage time. Typically, the shelf time of respirators is 5-10 years defined by the manufacturers.

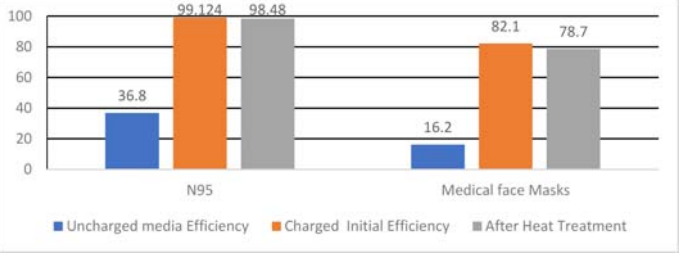

Fig. 3. Comparison of FE of uncharged, before and after heat treatment of charged media.

4. Discussion of disinfecting SARS-CoV-2 virus and the electret charge decay

4.1 Effect of Elevated Temperatures

The European EN143, and EN149 respirator certification standards require a respirator to meet their specifications after the pretreatment at 70 °C for 24 hours. There was only 0.6% decrease in FE for a 99%-level media as shown in Fig. 3 (L), which is the media commonly used for N-95, a decrease of 3.4% on the media for BFE 95 as shown on the right side in the same figure.

Disinfection research showed that a treatment at 56 °C for 30 minutes kills SARS CoV-1. A preliminary results[10] showed that a treatment at 70 °C for 30 minutes kills SARS-CoV-2. This treatment does not affect the charge decay.

It is validated[11] by National Institutes of Health (NIH) that 70 ℃ dry heat for 60 minutes has a 6 log reduction of SARS-CoV-2. French research group[12] showed the killing rate of COVID-19 at 56 °C for 30 minutes, 60 °C for 30 minutes, and 92 °C for 15 minutes, prepared using different lysis buffers. We conducted an experiment using 92 °C, dry and moist heat, to treat a type of N95 respirator. Shown in Table 2 are the average performance, insignificant loss of FE, of four respirators for four-time treatments at the interval of 24 hours each time on the same respirator.

Table 2. Before and after multiple-time treatments under dry and moist conditions at 92 °C.

Heat Treatment (92 °C)	Dry heat		RH 85% heat	
(one hour each treatment)	FE (%)	R	FE (%)	R
Before treatment	99.65	10.3	99.676	10.3
After 1st treatment	99.35	10.4	99.42	9.4
After 2nd treatment	99.47	9.4	99.54	9.3
After 3rd treatment	99.07	9.5	99.26	9.4
After 4th treatment	99.17	9.5	99.3	9.4

Suspension of the respirators in an oven for heat treatment as shown in Fig. 4 is recommended to obtain the heat uniformity and to avoid the contact with each other and with the proximity of metal materials that may have much higher temperature than that of the air.

Fig. 4. Suspension of respirators for heat treatment in the oven (Picture provided by Liching Liu).

4.2 Treatment at Higher Temperatures, by Steam, and by Boiling water

Earlier tests using a high pressure steam, or Autoclave, at 121 °C for 3 minutes indicated little or no signs of the electrostatic charge decay on the filter electrets.[13] This method is commonly used to sterilize new face masks for aseptic applications since before and after making, they might have attracted some bacteria or virus from the environment. The filtration performance of face masks by the treatment of atmospheric steam for 30 minutes as shown in Table 3 is in the acceptable range, in which 85.2% as discussed in Section II.2 exceeds the FE requirement of 80% of submicron particles for BFE 95. Included in the table that an N95 respirator having an initial FE of 99% is predicted[14] to be 97.5% by the above steam treatment for 30 minutes.

Table 3. Performance of masks by atmospheric steam treatment.

Steam treatment	Experimental	Theoretical prediction
Initial FE (3-fold medical mask)	93.2%	N95 (99%)
Steam for 5 minutes	91.7%	98.5%
Steam for 30 minutes	85.2%	97.5%

Face masks, especially N95 Respirators for maintaining their integrity of the proper edge fitting during use, are made of multiple types of materials. The composed materials are likely deformed under the steam treatment. High temperature may cause deformation of the face masks leading to the failure of edge tight fitting on N95. Fig. 5 shows the breakage of a medical mask and the deformation of N95 after the atmospheric steam treatment for 3 minutes. This type of medical mask made of pulp tissue as outer and inner veils as well as the middle filtering layer is unauthentic. An authentic medical mask is made of three plies of nonwoven fabrics. The deformation treated using boiling water had the similar results as treated by steam.

Fig. 5. Breakage of a medical face mask (left) and deformation of two N95 (right) after atmospheric steam treatment for three minutes.

Medical mask is a three-fold structure made of nonwoven fabrics, lack of edge tight-fitting requirement. Deformation without breakage does not affect its performance to stop the big droplets. However, the deformation of an N95 will lose its tight-fitting capability. After treatment, the edge tight fitting on an N95 needs to be examined and checked for reuse.

4.3 Treatment using acohol, soap and bleach agent/ solution

The second method validated by NIH is the heat treatment

of 70% alcohol that kills SARS-CoV-2. However, alcohol is inappropriate for sterilizing the masks due to the fact that it erases the charges and hence tremendously reduces the FE as shown in Table 4. Isopropyl alcohol (IPA) has been used by ASHRA52.2,[15] European EN776,[16] and ISO 16890[17] to erase the charges of an electret before the FE testing of a filter.

Table 4. Performance after alcohol treatment (provided by the industry and approved by Tsai).

Initial Filtration Efficiency (3-fold medical mask)	93.2%
After Immersion in medical alcohol	67.0%
After treatment with saturated IPA vapor according to ISO	47.4%
After washing by hand with soap/water for 2 minutes	54.0%

The N95DECON consortium[18] informs that the commercial bleach solution or disinfectant with bleach content is inappropriate for the decontamination of N95 owing to the fact that the content and the capability of the commercial bleach solution to inactivate the virus vary and the inhalation of its residue is harmful to health.

4.4 H_2O_2 treatment

FDA has approved the use of vaporous (vaporized) hydrogen peroxide (VHP) to inactivate N95 for 2 hours. It is also validated by NIH. N95DECON indicates that H_2O_2 vapors condense on N95 that kills SARS-CoV-2. As shown in Table 5, our investigation depicts that there was little charge decay by immersing N95 in a 3% H_2O_2 solution.

Table 5. Performance of N95 before and after the treatment of H_2O_2 solution.

N95	Before H_2O_2 treatment		After H_2O_2 treatment and dry*	
Respirators	FE (%)	R (mmH_2O)	FE (%)	R (mmH_2O)
1	99.629	8	99.562	7.7
2	99.648	8.1	99.579	7.9
3	99.674	7.9	99.583	7.7
4	99.67	8.2	99.582	8

*: After 3% H_2O_2 immersion treatment for five minutes. The respirator is wetted out.

Dripping dry for 24 hours, not quite dry, then heat treated at 70 °C for 30 minutes

4.5 Ozone(O_3) and the sun light treatments

The ozone treatment of N95 was conducted in an enclosed van as shown in Fig. 6 (L). After the ozone and sun light treatments, there was no signs of the FE decrease as shown in Table 5. However, cracks were observed on the natural rubber ear loop as shown in Fig. 6 (R). These crack phenomena were reported in previous literatures as well.

Fig. 6. Suspended N95 (L) for ozone treatment for 25 minutes, cracks on rubber band (R).

Table 5. Before and After Ozone and Sun Light Treatments.

Treatment	Before		After	
	FE (%)	R	FE (%)	R
Ozone (O_3), 25', Sample1	98.17	9.5	98.46	9.6
Ozone (O_3), 25', Sample2	97.6	9.5	97.86	9.7
Sunshine (70F) for 3 days (8hr/day)	97.89	9.1	98.15	9.3

Ozone treatment is not recommended by N95DECON owing to the fact that the inhalation of ozone residue on the respirator is harmful to human health. No data show the duration of sunshine exposure to kill COVID-19, although it does not have the FE decay for a period of time, e.g., three days in this experiment.

4.6 Round robin rotation

It was reported by the New England Journal of Medicine (NEJM, March 17, 2020)[19] for the durations of SARS-CoV-2 virus survivability on the surface of different materials as summarized below. The experiment was conducted at 70-73°F and a relatively humidity of 40%.

1. Suspended aerosol in the air for 3 hours
2. Copper surface for 4 hours
3. Cardboard for 24 hours
4. Stainless steel for 2 days
5. Plastic surface for 3 days.

The above aerosols were maintained suspended by the experimental design. In an actual environment, fine droplets will settle on the ground within a short distance. Therefore, it is important to comply with the 6-foot social distancing and to wear a mask.

It is believed that the virus needs a host-a cell in this case, to survive. The used and contaminated respirator will get dry in a good ventilation space for 2-3 days. The cell should die when it gets dry so does the virus. If so, based on the results of NEJM, it is an educational suggest to label four face masks as #1, #2, #3 and #4. Wear one alternatively each day in sequence. The first used one has got dried during these four days. N95DECON conservatively recommends to prepare seven respirators and wear them in the numerical sequence each day from the first to the seventh day.

4.7 UV light and gamma irradiation

UV and Gamma Irradiation are commonly used for material sterilization. However, the MB electret is made of polypropylene (PP) material, which is sensitive to UV light due to the fact that under the UV excited energy, the lone pair electrons on the methyl side group will attack and lead to the breakage of the main molecular chain causing the brittleness and the strength loss of the material. The charges might be degraded during the UV treatment process. Therefore, the losses of charges and the material strength by the UV dose and exposure time to kill COVID-19 need to be further investigated. The UV dose and exposure time to kill different bacteria and virus and the accompanying loss of material strength have been reported.[20,21,22]

The fourth method validated by NIH is the treatment using UV light of 265-285 nm in the wavelength for 100 minutes, to effectively inactivate SARS-CoV-2. The N95 after the treatment passes the fitting leakage tests.

Gamma irradiation has a higher energy intensity than UV light. A manuscript reported,[23] to be peer-reviewed and published, that there was a serious damage of masks made of PP material by Gamma irradiation.

4.8 Ethylene oxide (EO)

The EO chemical is commonly used for sterilization of medical polyphenyl ethers (PPEs) such as isolation and surgical gowns. However, after the EO treatment, inhalation of the EO residue on a respirator is harmful to human health. It is not recommended and therefore no data has been reported to do the mask sterilization using EO.

4.9 FE of N95 respirator before and after use

Generally, a new face mask is used to study the effect of different treatment methods on the charge decay or FE. There is no reason to do the sterilization and to reuse the mask if its FE has been distorted after each use by the exhalation vapors accumulated in the mask. It was found that there was no decrease of the FE after the use of the mask for eight hours as shown in Table 6.

Table 6. FE of N95 Respirator Before and After Use

N95	Before use		After use		Hung dry then 70 °C, 24 hours	
	FE (%)	R (mmH_2O)	FE (%)	R (mmH_2O)	FE (%)	R (mmH_2O)
Wearer 1	99.787	9.3	99.757	9.4	99.746	9.3
Wearer 2	99.774	7.4	99.767	7.4	99.742	7.3
Wearer 3	99.869	8.2	99.77	8.2	99.715	7.9
Wearer 4	99.852	7.5	99.787	7.6	99.710	7.2

Donning duration 8 hours

4.10 Home made mask materials

Due to the sudden outbreak of COVID-19 in the USA, there has been a serious shortage of face masks. Homemade face masks are suggested by CDC to wear in crowd. The charged microfiber PP nonwoven material used for making face masks is not available in the market. The MERV 14 filter for home AC filter having an FE similar to BFE95 is an ideal choice as the middle layer between two cloth layers for a homemade face mask. If the MERV 14 is not available, MERVE 13 filter material is the second choice. Based on the FE and hydrophobic considerations, shop towel, a fibrous structure likely to be hydrophobic, is another choice. However, pulp texture like coffee paper or paper towel is not suitable because of their hydrophilic property that spreads the virus across the media to possibly contaminate the nose and the mouse and their low breathability for making or for inserting inside the cloth layers as home-made DIY masks.

4.11 Use of high FE, low PD media

Corona charging is a method to make effective air filter media. Besides, triboelectrification using water, which simulates the formation of lightening during a storm in nature due to the rigorous friction of highly pure water droplets with the air, can achieve a level of 20-fold FE improvement compared with the uncharged media suggesting that the breathability of a mask is doubled making the wearer more comfortable and the decrease of oxygen level inside a respirator is expected to be greatly improved. This technology is patent pending.[24]

5. Conclusions

High efficacy and high breathability are achieved using corona charging of MB microfiber fabrics as the media for medical masks and N95 respirators to fight corona virus COVID-19. The embedded charges in the fibers are quasi-permanent. The masks thus made can last a shelf time for at least 10 years or longer. The FE and the integrity of the masks are maintained by the sterilization using elevated dry or moist heat, peroxide, and possibly UV for multiple times. It is possible as well to reuse the masks after hanging dry for four-to-seven days. Newly developed hydrocharging technology can provide equivalent or higher efficiency at 50% reduced weight of material and doubled breathability.

Supporting information

Available at: https://dx.doi.org/10.30919/es8d1110

Conflict of interest

There are no conflicts to declare.

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